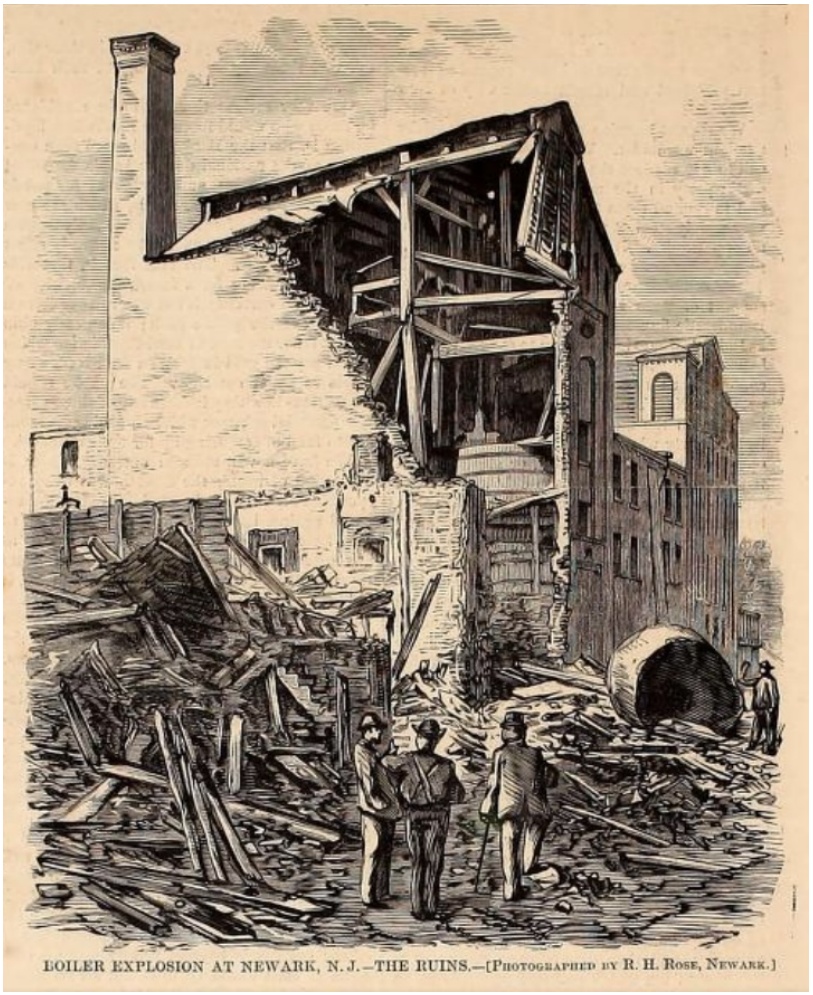
CHAPTER 11: Boiler structure failure

MOST COMMON FAILURES IN BOILER STRUCTURES

The most common causes of boiler failures do not occur due to faults in the pressure vessel (metal shell, plates, domes, headers, and tubes), since these are built under strict construction standards (both in terms of design, which must respect the internal circulation of water or steam, the mechanical effect of pressure, the thermal and chemical conditions to which the material is subjected, as well as its composition, shaping, welding, stress relief, hydraulic testing, non-destructive and destructive testing (in case of doubt), etc.).



BOILER EXPLOSION AT NEWARK, N. J.—THE RUINS.—[PHOTOGRAPHED BY R. H. ROSE, NEWARK.]

Most boiler failures are caused by various auxiliary elements related to boiler operation and safety (electrical, electronic, mechanical, pneumatic, and chemical) and human error (when the boiler operator's training is inadequate).

Therefore, we can say that technicians working with boilers must not only have machines or engineering background but also "aptitude," which comes from experience and a genuine interest in boilers.

Since the "boiler operator" is the person who is constantly involved in the operation of the boilers, special attention must be paid to their professional and personal development, considering all aspects of their responsibility, in which human life and the factory's finances are at stake (the boiler is a place where fuel can be burned improperly, causing significant losses).

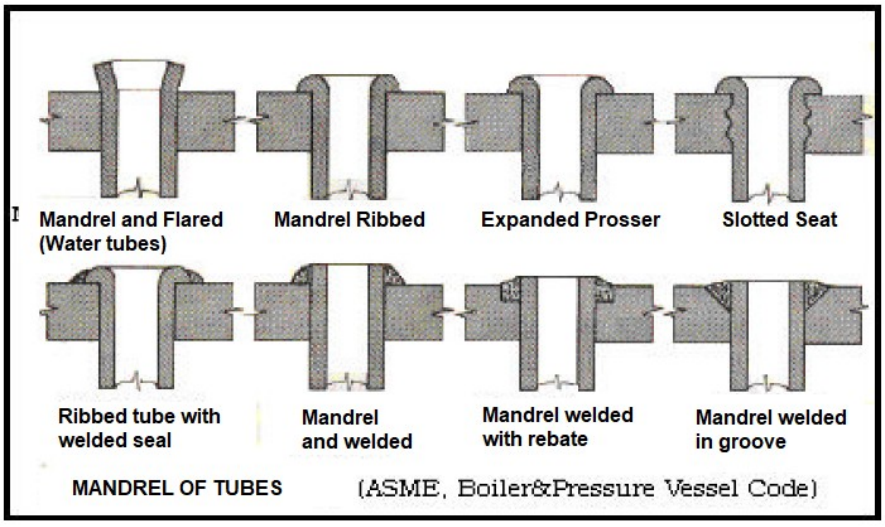
But in addition to efficiency, there is the need for most processes to continue uninterrupted (when a factory runs out of steam, many things are lost, not only lost profits, but also wages and salaries, and other inputs such as raw and semi-finished materials. In many cases, I believe there is no greater loss than forced shutdowns).

PROBABLE CAUSES OF BOILER TUBE LOOSEN IN FIRE-TUBE BOILERS:

The primary function of the tubes in fire-tube boilers is to generate steam from hot water (T > 100°C 212°F) and to provide structural support by holding the plates in position.

Therefore, the tube-to-plate connections must not only be leak-proof but also mechanically strong (maintaining the distance between the plates and preventing pressure from deforming them).

For these reasons, the tubes must be mandrel-grooved, welded, or flanged according to established standards.

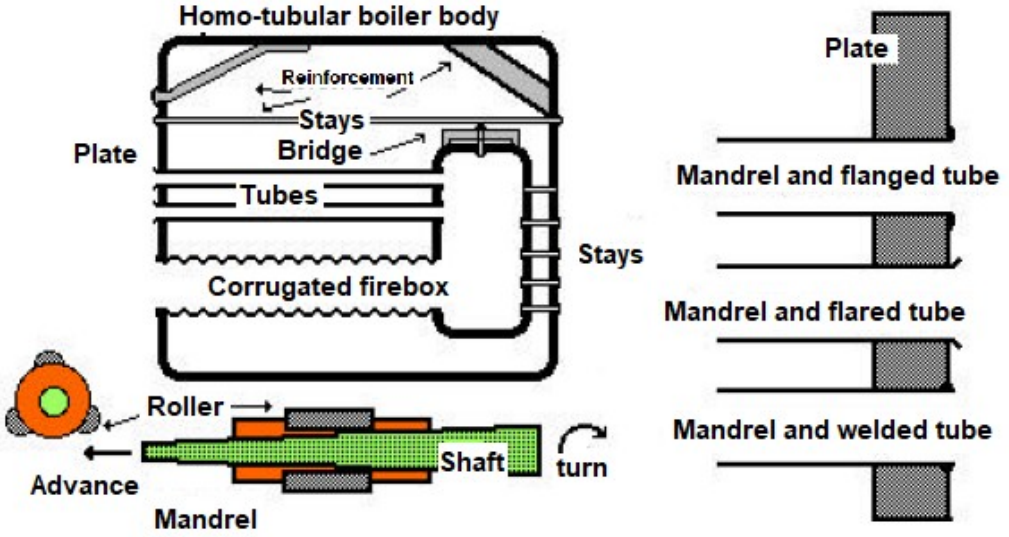


Meeting the above requirements, loosening of the tubes at their connection to the plates should not occur, but in reality, it does.

We can identify several causes for this loosening, which are usually attributed to **improper boiler assembly or inadequate material quality.**

The common element in all the failures we will mention is the expansion of the tubes and plates, which, due to temperature changes or differentials, causes abnormal stress between them.

For every 100°C (212°F) temperature variation and for every meter of iron material, there is an expansion of approximately 1.2 mm.

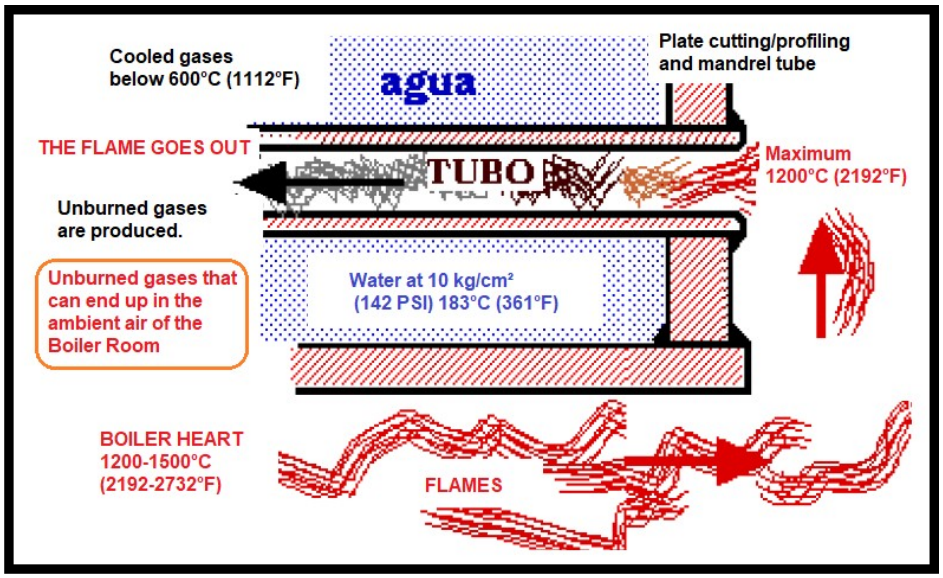


Let's look at the most common failure causes:

1-ENCLOSED BOILER:

If the tubes are embedded (the plate will usually be as well), the metal temperature increases, causing the tubes to expand more than normal (the tubes lengthen more than the boiler).

This greater-than-normal expansion puts stress on the joint between the tubes and the plates, which not only causes the joint to break but can also fatigue the plate (repeatedly deforming it beyond the material's limits), causing it to crack.



The plate itself will be overheated, which will raise the temperature in the mandrel area, facilitating loosening of the mandrel, weld breakage, and probable plate cracking (thermal fatigue: repeated exposure to high temperatures).

This, combined with the excessive stress on the tubes and plates, accelerates the aforementioned process.

The increased rate of vaporization accelerates this process (due to the increased temperatures from forced combustion), as do the chemical conditions of the water (high pH, high content of dissolved and insoluble solids, excess free alkalinity, etc., all of which increase the number of steam bubbles inside the water).

A boiler in these conditions (scaled or full of sludge) should be cleaned chemically and mechanically.

2-BOILER WITH POOR WATER CIRCULATION:

If the boiler is full of sludge or scale buildup that impedes proper water circulation, the tubes and plates are subjected to abnormal temperatures (heat transfer surfaces), causing differences in expansion, greater than normal expansion, thermal fatigue, plastic deformation (due to loss of strength from high temperatures), etc.

3-BOILER WITH CIRCULATION CUT OFF DUE TO LOW PRESSURE AND HIGH FIRE RATE:

This category includes boilers where pressures are allowed to drop excessively with a high fire rate or high flame (attempting to recover pressure).

This causes poor cooling of the tubes and plates, especially at the junction of the tubes with the hottest plate (causing insulation of the hottest plate due to larger steam bubbles as the pressure decreases, preventing proper contact between the water and the metal for adequate cooling).

Operation should be based on the design differential pressure (for example: design pressure shuts off the high flame - 10% below this pressure ignites the high flame or the burner), or by shutting off less important fuel consumption if normal pressure recovery is not possible.

If for some reason it is necessary to work with low pressures (for example 50% below the design pressure) it is advisable to reduce the maximum fire rate to an appropriate value.

These concepts will depend on the type of boiler and its use.

Some boilers already come with double protection for these situations: they have a pressure switch that only allows the high flame to activate when the pressure is above a certain value, meaning that at low pressure it is impossible to activate the high flame.

Another protection measure can be a restriction in the steam outlet valve (diaphragm or orifice plate), so that when the pressure drops and the volume of steam per kilogram increases (specific volume), the pressure inside the boiler tends not to decrease because the steam cannot escape easily (increased pressure drop in the outlet valve).

This also applies when starting the boiler; that is, it must be lit and heated slowly with a low flame until the working pressure is reached (by venting air through the atmospheric valve until sufficient steam is released; otherwise, the heating will be incomplete, as the pressure will be reached at a lower boiler temperature and there will be insufficient internal circulation for heat distribution, resulting in cold spots in the boiler water).

When supplying steam for use in the plant, do not allow the pressure to drop too low. If necessary, shut off some steam outlets and do not force

combustion when the pressure has already fallen below 50% of the working pressure.

4-FEEDING WITH COLD WATER AND RAPID HEATING:

In these cases, effects such as those already described occur, exacerbated by sudden contractions and expansions.

Boilers should be fed with the hottest water the feed pump allows, without cavitating (this improves boiler response, reduces dissolved oxygen, increases momentary nominal capacity, etc.).

Start-up should be slow until the operating pressure is reached, heating the feedwater as quickly as possible. Then, steam should be applied gently to avoid a sudden drop in pressure, as well as carryover and line heating with sudden surges.

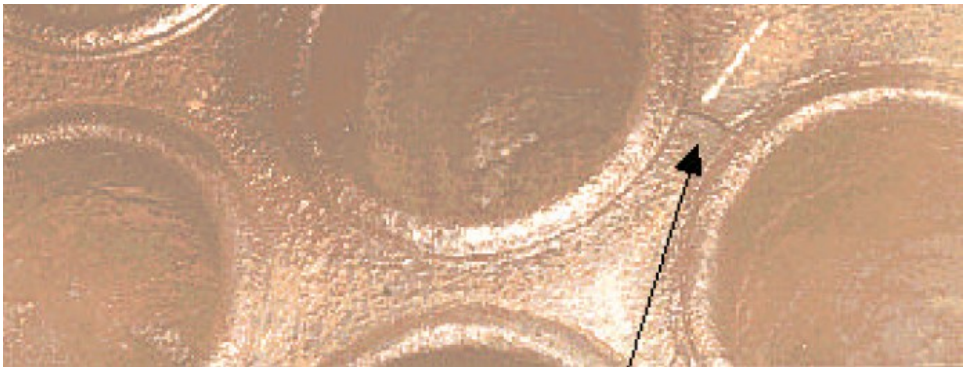
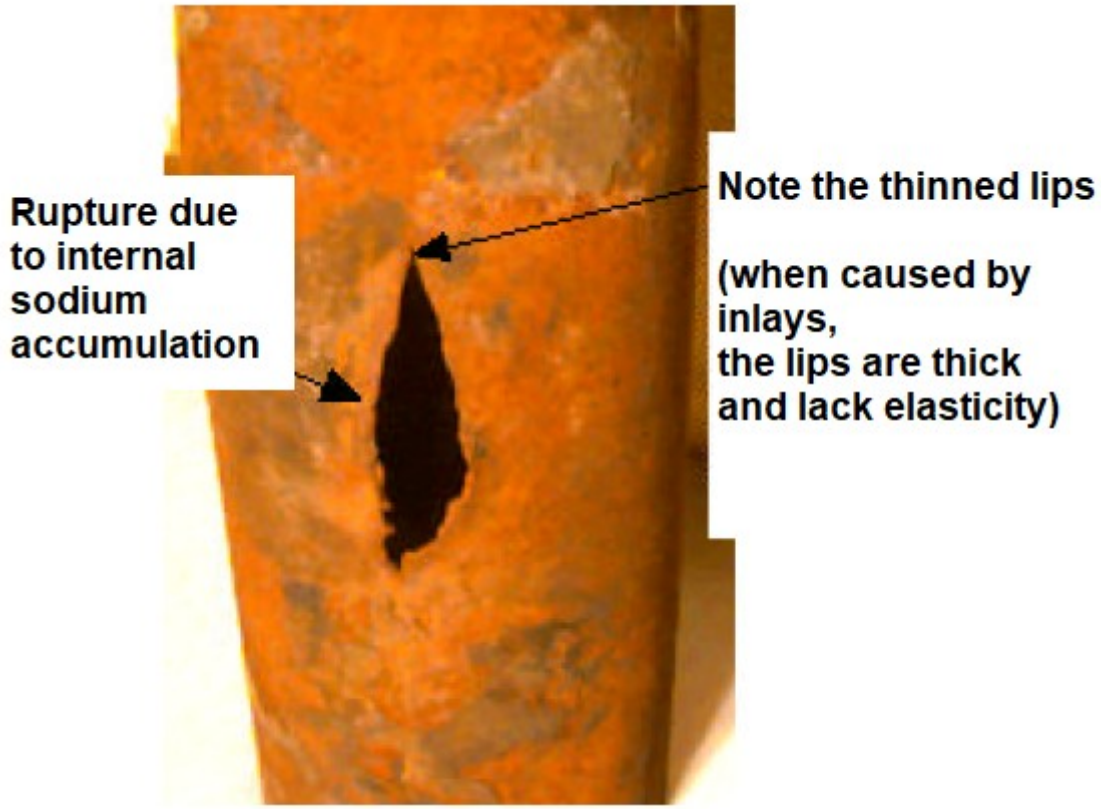


PLATE CRACKED BY THERMAL FATIGUE
caused by low steam pressure with maximum combustion.

The lower plate has developed a crack between the tube holes (which are subjected to the stress of the mandrel), due to insufficient cooling caused by the boiler operating at very low pressure and maximum combustion.

The vapor bubbles that form against the plate and tubes increase in size as the pressure drops, pushing away the cooling water, which causes thermal fatigue.

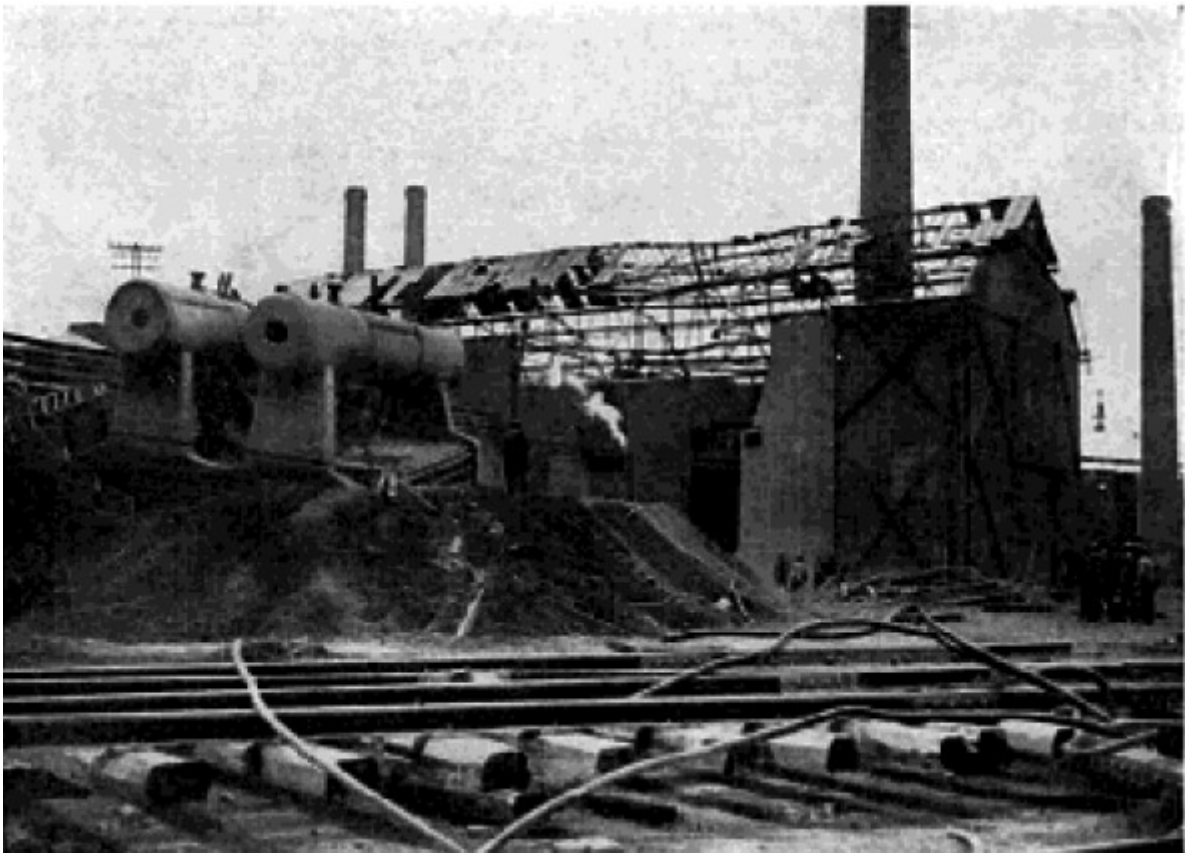
This lack of cooling not only increases when the pressure drops or combustion increases, but also under certain physicochemical conditions of the water, the bubbles increase in size (high pH, high dissolved or suspended solids, organic contamination, scaling, etc.).


Rupture due to internal sodium accumulation
Note the thinned lips
(when caused by inlays, the lips are thick and lack elasticity)

5- CHEMICAL CONDITIONS OF WATER:

The chemical conditions of water are linked to all the phenomena mentioned above. Essentially, the order of alteration is determined by: high alkalinity (primarily hydroxides), contamination with organic materials (fats, oils, milk, sugars, etc.), and total dissolved solids (plus suspended solids). These limits must be carefully managed.

These conditions affect the boiler's operation, since exceeding the permissible limits for each boiler—entrainment, level variations, and even the effect of spontaneous boiling (where the heat transfer surfaces are enveloped in steam rather than water)—can not only loosen the tubes but also allow overheating of the hottest plate and even collapse the furnace in high-speed boilers (those with high heat transfer rates).



Boiler room explosión
Phoenix pipe manufacturing plant after a boiler explosion in Düsseldorf-Derendorf, Germany.
The incident occurred on November 12, 1893.

6-OPERATING PROCEDURE:

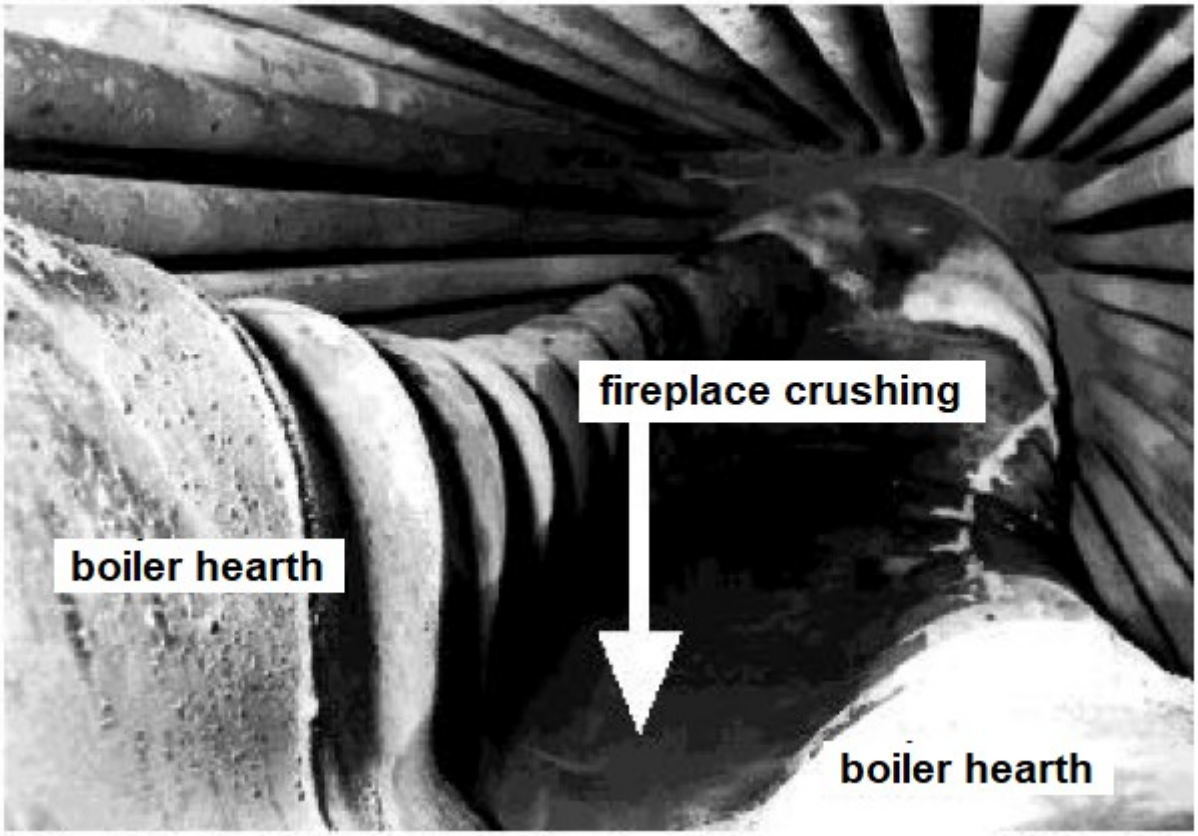
Never allow the water level to fall below the minimum level:
Turn off the heat and close the steam outlet if the boiler cannot be supplied with water (power outage, lack of water, pump failure, end of the workday, etc.).

Operations involving large steam valves must be carried out smoothly, never hastily or abruptly.

First, open a bypass valve (a small valve connected in parallel) to achieve initial heating of the lines, the steam distribution pipes, and the equipment to be supplied, including the steam consumption installations. This allows for the balancing of the boiler's vaporization process (water level inside, water circulation, pressure recovery, etc.).

A violent opening of a valve of a certain size can cause a large amount of water to be drawn in with the steam, a decompression inside the boiler that artificially raises the water level (you can see the levels rise, but in reality it is the same amount of water inside the boiler that rises due to the bubbles as the boiler decompresses), leaving the heat transfer surfaces without enough cooling water: steam is produced that insulates them, causing loosening of tubes, cracks in plates, and even overheating of the furnace.

FIREPLACE CRUSHED DUE TO APPARENT WATER LEVEL FAILURE



Poorly designed or operated purge (blowdown) valves—that is, blowdown valves located in areas where their activation disrupts water circulation within the boiler during high steam generation—cause localized overheating.

Bottom purges (blowdown) valves should not be operated at high steam generation rates: they are ineffective at removing sludge and also risk interrupting circulation within the boiler (continuous blowdown should be used to maintain acceptable levels of dissolved solids, pH, alkalinity, etc.).

The mud collectors on the walls of a cooled furnace (such as boilers with chapels, gas generators, water-tube furnaces, etc.) should not be purged with medium and high vaporization rates, and should be purged at times of very low or zero vaporization (fires extinguished with pressure in the boiler).

Always check that the bottom and level drains are working correctly, listening for the "noise" produced by the water flow and the flash steam that occurs when draining.

If the drain opens and does not perform its function of removing water with sludge, this sludge will accumulate and cause an internal circulation problem or blockage of the level controls, resulting in an accident.

COMMON CORROSION IN BOILERS

Localized Corrosion:

Fire-tube boilers are susceptible to pitting (localized corrosion) of the upper tubes when they are improperly shut down. The same occurs in water-tube boilers in the upper drums and superheaters.

The upper tubes, being closer to the water level, are exposed to the action of oxygen that enters when the boiler is shut down.

When the boiler water temperature drops below 100°C (212°F), a vacuum is created, allowing oxygen-containing air from the atmosphere to enter. This oxygen causes localized corrosion in specific areas, which, once it begins, is facilitated by the pitting structure itself.

If the boiler reaches a certain internal temperature, corrosion increases because the temperature accelerates chemical reactions (this occurs when the boiler receives steam leaks through the steam outlet valve from other boilers in operation).

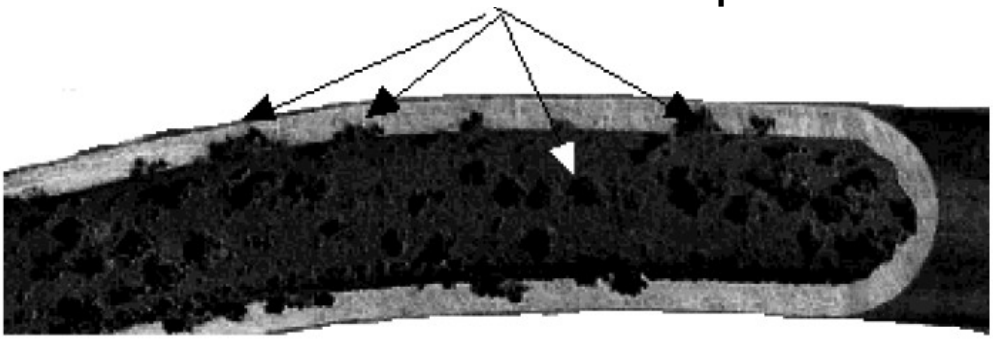
If the boiler is not chemically treated or is not even slightly scaled, this corrosion also accelerates (the use of softened or demineralized water without subsequent chemical treatment also facilitates this corrosion).

To prevent this corrosion, the boiler must be chemically treated with an oxygen scavenger (and have a suitable pH, above 10.5), and the water level must be maintained to prevent air from entering the boiler (keep it flooded with a water seal).

See the boiler maintenance chapter 7.

This type of corrosion also occurs in water-tube boilers, primarily affecting the steam drums and their steam separator accessories, as well as steam superheaters that are not properly flooded during shutdowns.

OXYGEN CORROSION ("pitting") WATER-TUBE BOILER
corrosion is localized in several points



Localized corrosion due to metal differentials:

Galvanic currents (actual electrical cells) are caused by the voltage that develops between different types of metals when they are submerged in boiler water. This water conducts electricity because it contains salts that dissociate into ions. For example, copper-containing materials tend to corrode tubes, casings, and plates made of special mild steels used in boilers.

Stainless steel and cast iron also behave like copper, but less strongly. These galvanic corrosion conditions are avoided by avoiding the use of metals that can attack iron, and also by the chemical composition of the water, which plays a fundamental role, conditioning the iron surfaces to resist electrical corrosion and preventing the iron from dissolving in the water.

In the past, zinc "sacrificial" elements—anodes—were placed in boilers so that the corrosion would attack them instead of the boiler structure.

It was later discovered that when the temperature exceeded 80°C (176°F), these electrodes reversed their polarity and, instead of protecting, could

attack the iron. Therefore, their use was discontinued.

Sacrificial ZINC anodes wrongly used years ago for corrosión protection,
today MAGNESIUM is better used.

In water heaters with enamelled iron tanks, these sacrificial elements are used, but instead of zinc, they are **magnesium rods. Magnesium provides slightly better protection above 80°C (176°F) in water heaters.**

Without the sacrificial element, if there were a small perforation in the enamel, the tank would perforate more quickly as the current concentrated at a single point, compared to if the tank were unenameled.

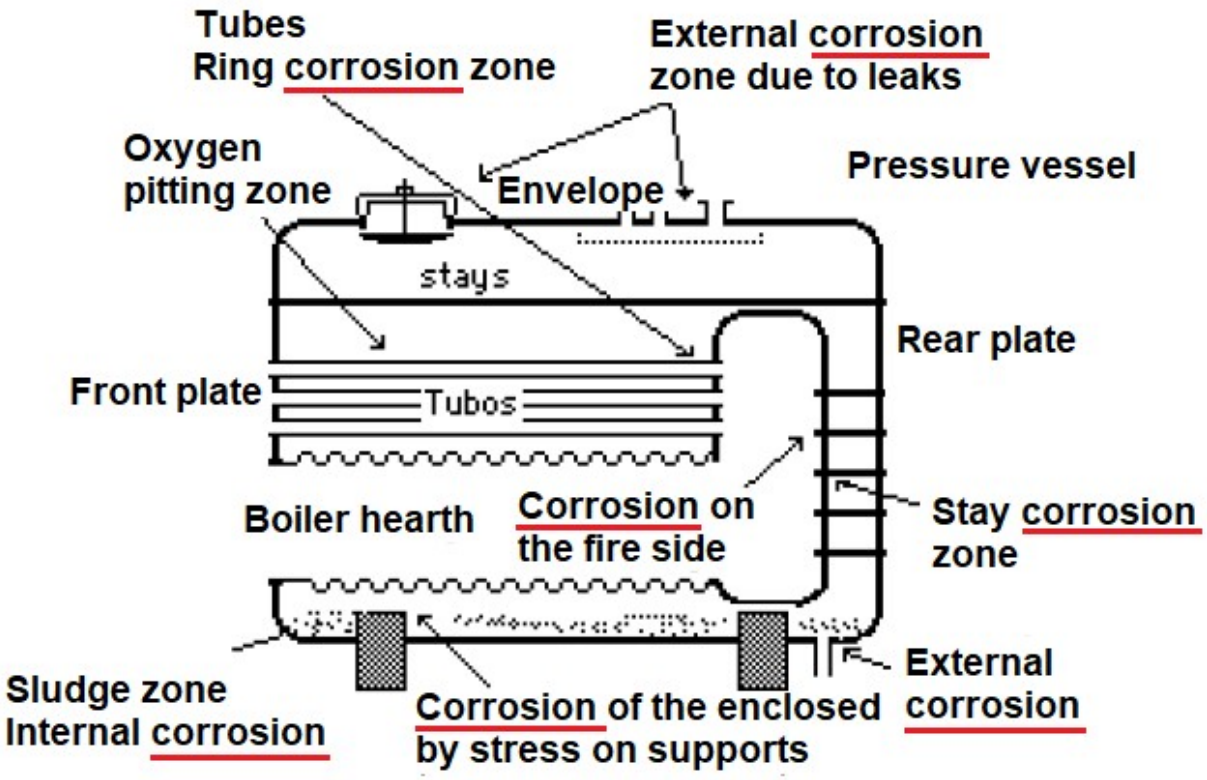
In addition to galvanic currents caused by metal differentials, we must consider others: external currents due to electrical and magnetic losses in electrical installations. **These must be avoided by ensuring proper electrical installation and correct grounding of electrical equipment.**

Other currents that cause corrosion are due to differential oxygen (called "differential aeration"), which is the difference in the amount of oxygen in the water between different parts of the boiler.

This can occur within the same "corrosion cell" -corrosion protrusion- or between a part of the boiler that is "covered with sludge" and the clean part, etc.

In this case as well, internal chemical treatment is essential, eliminating oxygen and preparing the metal surface.

This includes periodic sludge removal or chemical cleaning to eliminate corrosion cells once corrosion has occurred, etc.



POINTS WHERE THE MOST SIGNIFICANT CORROSION OCCURS

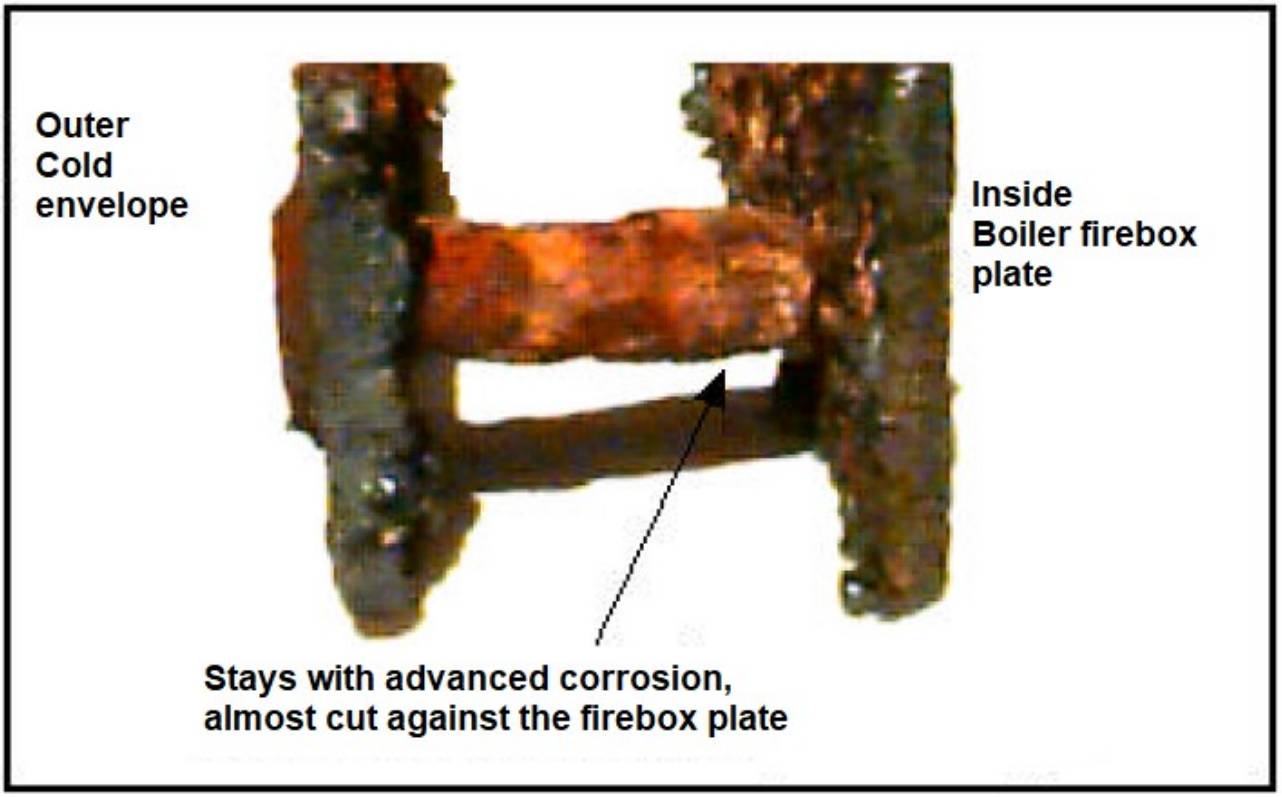
Another instance of this electrical differential: this occurs due to the temperature difference between the metals that make up the boilers.

Here too, potential differences arise that cause corrosion. This case includes the corrosion of the welded stays between the combustion chambers and the shells of some types of fire-tube boilers.

Since the metal of the combustion chamber is much hotter than the metal of the shell (of the pressure vessel, not to be confused with the outer sheet metal that acts as a casing), it produces a voltage difference that creates electrical conduction through the boiler water. This causes corrosion that tends to cut the stays near the hottest area.

This failure is very common in low-pressure heating boilers that have many stays (due to their flat shape) and because their water is not usually chemically treated.

It is important to keep this detail in mind when inspecting boilers of this type: inspection of the "stays" for corrosion against the hottest area.



STAYS SEVERE CORROSION FIRE-TUBE BOILER

In fire-tube boilers, the most common type of corrosion occurs on the tubes, near the "hottest plate" area.

This corrosion is called "ring corrosion," and it is generally attributed to the fact that scale tends not to form on the tubes in this area, which is why it corrodes.

However, it should also be considered that when corrosion is present, scale cannot form on this surface.

With proper internal chemical treatment, this type of corrosion is reduced to a minimum.

Corrosion caused by differences in stress or force on the metal must also be considered in these cases.

These cases are generally found in the areas where the supports or "legs" of fire-tube boilers rest (this also occurs in boilers where a "free" expansion gap has not been left between the support "legs," since for every meter of boiler between legs there is an expansion of 1.2 mm per meter for every 100°C (212°F) increase in temperature).

These areas should be monitored from inside the boiler. In addition to these cases, stresses caused by welds that have not been properly relieved by annealing the boiler must also be considered. Internal chemical treatment is important to reduce their effect.

Softened water, distilled or deionized water, and rainwater: if not properly chemically treated, they accelerate all the types of corrosion we've discussed.

Corrosion in riveted boilers. Although boilers are no longer made with rivets, some riveted boilers (over 50 years old) still exist.

The problem with these boilers is that the rivets "sever" for various reasons, and sometimes this condition (very dangerous) is not visible.

One reason they shear is that they are subjected to two stresses: shear and tensile. This causes rivet fatigue, which is accelerated by the presence of concentrated salts in the boiler water that penetrate the joint, especially what is known as "caustic embrittlement," that is, the presence of large amounts of sodium, which is very common in softened well water.

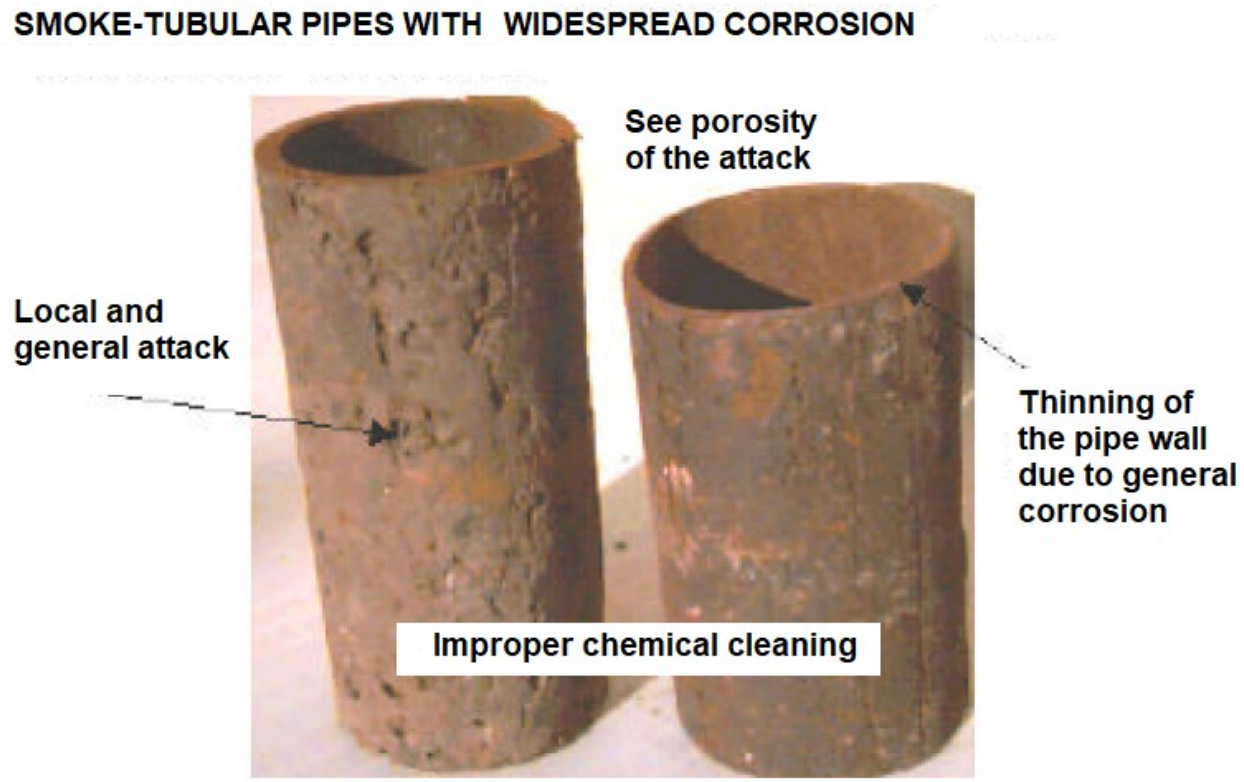
This situation is very dangerous, as the rivets gradually break down and sometimes no leaks appear to "reveal" them (the rust from so many years seals these leaks).

One way to determine this is through non-destructive testing (previously, some rivets were removed to inspect their condition, but since nowadays there are no operators who know how to properly rivet a new rivet in place, much less weld them, this is not a good solution. Non-destructive testing is better.

A "homemade" test involves striking the rivet with a ball-peen hammer (quite forcefully) while the boiler is under hydraulic pressure (working pressure but

100% water pressure, without steam or air inside the boiler to prevent an accident if the riveted joint breaks). If the rivet is cut, it will generally leak water upon impact.

Unfortunately, there is not much awareness of this problem, and sometimes it is advisable to decommission the boiler (which are generally very inefficient, and the cost of a new boiler is quickly offset by fuel savings).


SMOKE-TUBULAR PIPES WITH WIDESPREAD CORROSION
See porosity of the attack
Local and general attack
Thinning of the pipe wall due to general corrosion
Improper chemical cleaning

SMOKE-TUBULAR PIPES WITH WIDESPREAD CORROSION

Generalized Corrosion:

Generalized corrosion generally occurs in the presence of contaminants: acids, organic matter (fats, milk, sugars, etc.) that decompose inside the boiler, forming acids.

Alkaline materials (high hydroxide alkalinity, contamination with sodas, process lyes, etc.) that raise the water's conductivity and pH above 11.5 also contribute. Some improperly used boiler treatment products (bisulfites) or excessively high chemical limits, such as high chloride levels, etc., promote this type of corrosion.

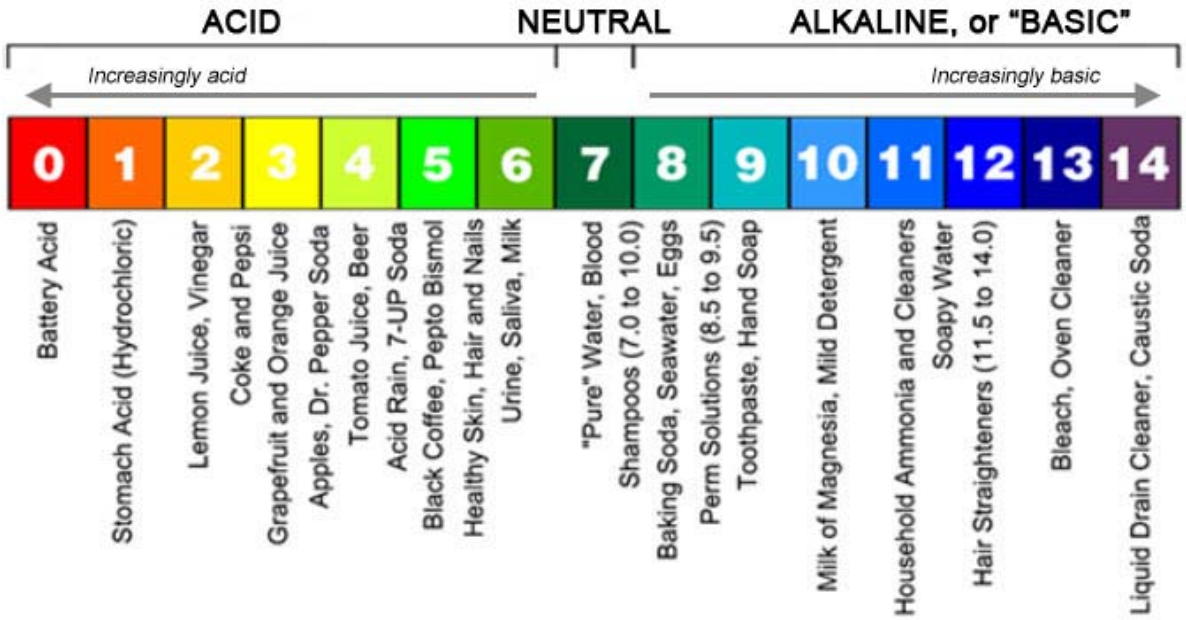
Generalized corrosion can attack the material in the hottest areas (fats, sugars, depending on the fuel used, etc.) or, in some cases, in the coldest areas (chlorides). The corrosion may manifest as direct attack on part of the material or as a failure to form the entire protective oxide layer on the metal surface.

In this latter case, the corrosion is so uniform that it is almost impossible to perceive with the naked eye (e.g., high pH levels: well water with "high alkalinity" softened in a sodium cycle with very high concentrations).

Boiler analyses are essential for detecting contamination.

Establishing the operating limits of the treatment process, as well as the appropriate internal chemical treatment for each feedwater condition, is fundamental.

In plants processing organic matter or contaminants, strict control of boiler water pH must be maintained very regularly (hourly, daily, etc.), since any contamination will immediately affect the pH (very easy to measure with pH paper, which is much more reliable than low- and medium-cost electronic meters, which are very difficult, if not impossible, to calibrate and adjust to their neutral pH point of 7.0).



Monitor condensate for pH, hardness, TDS (Total Disolved Solids), sugars, etc., although some of these contaminants may not affect the TDS or pH of the condensate.

Often, they will be noticeable by the formation of "foam" or rapid changes or fluctuations in levels.

When connecting digesters or other equipment, it is advisable to install check valves to prevent the backflow of contaminants through the steam lines when a vacuum or reduced pressure occurs when the steam is shut off or the boiler is turned off.

In the case of heating highly polluting products, especially those with minimal condensate (such as fuel oil heaters), it is preferable to discard the condensate, as its recovery could cause significant damage if the heating coils rupture.

One particularly important case to consider is the boilers used for heating swimming pool water (whether freshwater or, even worse, saltwater), given that pool water has a high chlorine content for disinfection.

Chlorine in the boiler circuit behaves less effectively than oxygen, which attacks the boiler when it's cold. Chlorine attacks both hot and cold water.

The presence of pool water in the boiler's feed circuit comes from both the condensate return line, due to the rupture of the heat exchangers (which are subject to serious corrosion problems from the pool water and the temperature, which increases corrosion and cracking), and contamination from the steam supply lines themselves.

When the boiler shuts down, it creates a suction effect as it cools below 100°C (212°F). This partial vacuum acts on the heat exchanger, drawing the pool water lost through the steam line into the boiler.

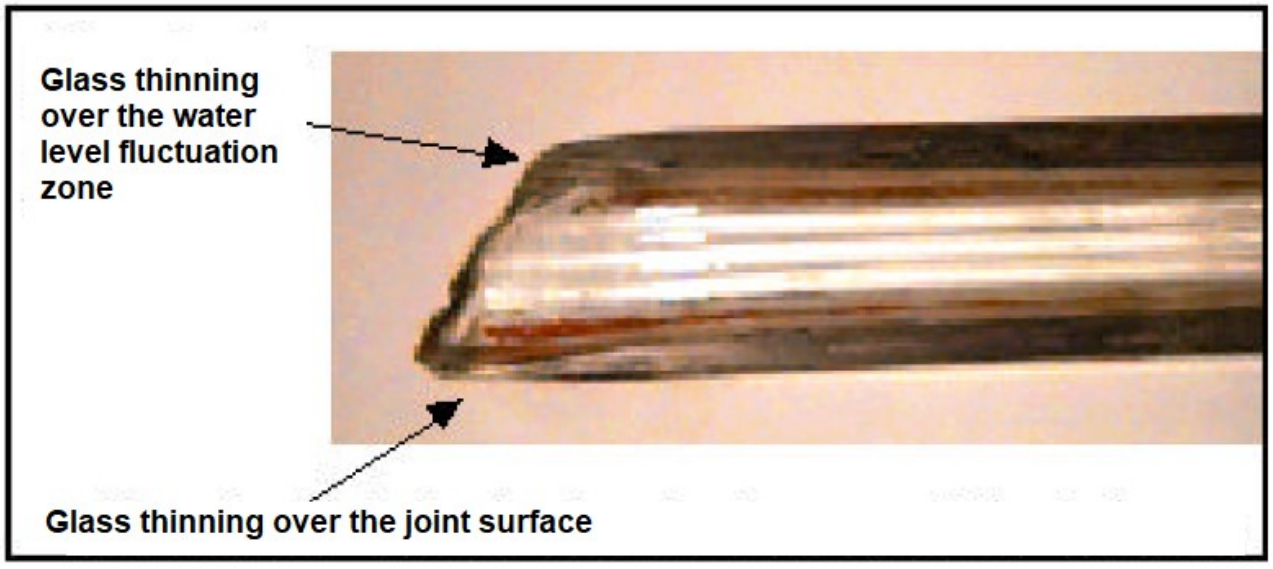
To prevent this, it is advisable to install check valves in the steam supply and also to install a vacuum breaker to prevent negative pressure in the piping.

Often, the heat exchanger loses more heat when it is cold because there is no backpressure on the steam side for the pool water, and cracks can even widen, as in the case of the tube-to-plate joint.

The heat exchanger material must be carefully selected, and the difference in expansion between the tubes and the shell must also be considered, as this is often responsible for the tubes loosening on the plates.

Corrosion on the boiler level gauges:

Corrosion can also occur on the level gauge crystals. This happens as pressure and the free soda content of the boiler water increase.



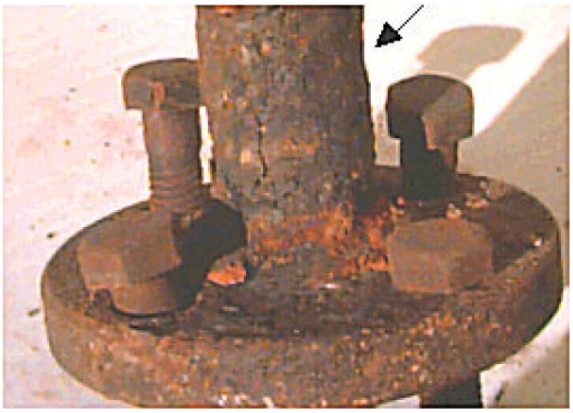
This problem is very common when using softened well water, due to the high alkalinity, bicarbonates, and sodium carbonates that decompose, leaving free soda in the boiler water and raising the pH to values above 12. Under these conditions, the free soda attacks the crystal, dissolving it in the area where the water level fluctuates, until the crystal breaks.

The solution to this problem is to limit the amount of soda through continuous blowdown or partial removal before feeding the boiler.

The glass panes should be inspected and replaced before they break.

One solution for high-pressure boilers, where the problem is more acute, is to use a mica plate to isolate the boiler water from the glass.

EXTERNAL CORROSION:



EXTERNAL CORROSION ON LEVEL CONTROL CONNECTION PLATE

External corrosion on boilers can be very serious and should be taken into account: it is often the cause of very serious accidents.

External corrosion is difficult to see because it is hidden by thermal insulation. Insulation is not easy to remove for inspection, since once removed it must be replaced.

This often leads to resistance from those in charge, such as the plant manager and other managers, who are reluctant to incur further expenses and costs.

Inspections should be carried out every few years (depending on the age and condition of the boiler) to examine the entire exterior of the boiler (the pressure vessel below the casing or housing).

These corrosive effects can also occur in the fire zone, generally beneath the refractory material or ash.

This can be due to the sulfur in the fuel and its condensation in cold areas, forming sulfuric acid; the condensation of pyroligneous acids in the case of firewood; the presence of acids resulting from incomplete combustion of gases that are not monitored with instruments; undetected water or steam leaks; and other factors.

High-temperature corrosion also occurs in areas where combustion directly affects the material and it cannot be properly cooled or protected.

These areas can include tube ends, welded stay heads, flat headers, or horizontal collectors exposed to fire, tubes or furnaces lacking good circulation, scale buildup, etc.

In some cases, it is necessary to measure thicknesses to assess corrosion, as the loss of metal wall thickness can be very uniform and not noticeable.

Superheaters are highly susceptible to this type of corrosion.

In the exterior area, it is important to consider water or steam leaks onto the boiler casing, due to valves or their fittings, which can seep between the insulation and the casing. This can cause corrosion due to humidity and oxygen in the air, accelerated by temperature.

Therefore, we must inspect the areas surrounding these components. Generally, hydraulic tests do not guarantee safety against an accident caused by external corrosion; these leaks are best monitored visually and by measuring thicknesses once they are located.

All the corrosion we've observed leads us to conclude that boilers that are out of service (shut down) would be better preserved if they were completely dry (using elements that absorb internal humidity or heating to keep them dry) and disconnected from any pipes that could introduce water or steam leaks, or from condensation dripping from roofs or rainwater.

The difficulty lies in the fact that putting this boiler back into service requires several hours of reconnection, filling with treated water, and a hydraulic leak test.

In the case of boilers stored "wet," meaning flooded with chemically treated water, where this method has been used to bring them back into service quickly, care must also be taken to prevent external water from dripping onto the boiler casing or chimney, as external corrosion can be significant during this period.

While heat accelerates corrosion, in this case, because the boiler is cold, the water trapped between the insulation or ash does not evaporate, keeping the wetted parts damp and causing permanent corrosion in these areas.

C.W.T. (Carlos W. Thomasset, 1945-2023) serving as chief engineer,
R.O.U. Presidente Oribe,
Uruguay oil tanker bought to Ishikawajima Harima Heavy Industries (1962)